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AERONAUTICAL RESEARCH LABORATORY

MELBOURNE, VICTORIA

Aircraft Systems Technical Memorandum 138

PROGRAMMABLE COCKPIT - FLIGHT DYNAMIC MODEL

by

M. Iob

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SUMMARY

The Programmable Cockpit has been developed as a low cost alternative to a full research simulator. It is intended for use in cockpit display design and layout studies and for crew workload and other human factors studies. With this system it is possible to quickly change the design or layout of a display and evaluate it under representative flight conditions.

A six degree of freedom flight dynamic model has been developed for the Programmable Cockpit. The model's development is described from its original form in the IBM PC-AT Simulator to its current implementation in the Programmable Cockpit. Its features and operation are described in some detail as well as its limitations. A brief overview of the Programmable Cockpit is also given. → (to p 2)

DSTO ARL MELBOURNE

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CONTENTS

NOMENCLATURE

α	Angle of attack
α_{turb}	Angle of attack turbulence input
β	Angle of sideslip
θ	Pitch attitude
ϕ	Angle of bank
ψ	Angle of yaw
$\tau_0..\tau_3$	Quaternion angles
$\tau_{0_n}..\tau_{3_n}$	Normalised quaternion angles
τ_n	Quaternion normalising factor
μ	Coefficient of friction or rolling resistance
$C_1..C_9$	Inertia constants
F_{norm}	Normal reaction force
F_r	Friction or rolling resistance
$F_{X_{stab}}, F_{Y_{stab}}, F_{Z_{stab}}$	Total force components in stability axes
$F_{X_w}, F_{Y_w}, F_{Z_w}$	Total force components in air–path axes
g	Gravitational constant
$I_{XX}, I_{YY}, I_{ZZ}, I_{XZ}$	Moments of inertia
K_{atten}	Turbulence magnitude attenuation factor
L, M, N	Total rolling, pitching and yawing moments in body axes
L_a, M_a, N_a	Aerodynamic rolling, pitching and yawing moments in stability axes
L_p, M_p, N_p	Propulsive rolling, pitching and yawing moments in body axes
$L_1..L_3$	Direction cosines
$M_1..M_3$	Direction cosines
$N_1..N_3$	Direction cosines
m	Aircraft mass
p	Body axes roll rate
p_{stab}	Stability axes roll rate
p_{turb}	Roll rate turbulence input
q	Pitch rate
q_{turb}	Pitch rate turbulence input
Q_w	Air – path axes pitch rate
r	Body axes yaw rate
r_{stab}	Stability axes yaw rate
R_w	Air – path axes yaw rate
$U_{body}, V_{body}, W_{body}$	Body axes components of aircraft velocity
$V_{N_{earth}}, V_{E_{earth}}, V_{D_{earth}}$	Earth axes components of aircraft velocity
$V_{N_{wind}}, V_{E_{wind}}, V_{D_{wind}}$	Earth axes wind components
V_t	Aircraft true velocity
$V_{t_{lim}}$	Limited aircraft true velocity
X_a, Y_a, Z_a	Aerodynamic forces in stability axes
X_p, Y_p, Z_p	Propulsive forces in body axes
$X_{g_{stab}}, Y_{g_{stab}}, Z_{g_{stab}}$	Stability axes gravitational force components

1.0 INTRODUCTION

The Programmable Cockpit has been developed as a low cost alternative to a full research simulator. It is intended for use in cockpit display design and layout studies and for crew workload and other human factors studies. With this system it is possible to quickly change the design or layout of a display and evaluate it under representative flight conditions. As a result the flight dynamic model was required to represent any given aircraft type with a reasonable degree of fidelity.

The Programmable Cockpit is a development of a small simulator which was implemented on an IBM PC–AT computer. In its current form the system represents the first stage in the development of the Programmable Cockpit (PC-1). The flight dynamic model has been significantly extended from its original form in the PC based simulator to its current state in the Programmable Cockpit. Section 2.0 describes the small PC based simulator and the flight dynamic model developed for it. Section 3.0 gives a brief overview of the Programmable Cockpit and the extensions made to the dynamic model. Finally section 4.0 discusses planned future developments to the Programmmble Cockpit and the flight dynamic model.

2.0 IBM PC-AT SIMULATOR

The flight dynamic model was originally developed to run in real–time on an IBM PC–AT. It forms the basis of the simulator which also produces a screen of typical aircraft flight instruments. The flight dynamic model has been programmed using Microsoft Pascal and the instrument panel was generated using the MetaGraphics Meta WINDOWS/PLUS graphics package.

The operator flies the simulator using a joystick and the flight information displayed on the instrument panel. An outside view was not provided as the computation time would have been excessive. A screen update rate of approximately 10 Hz was achieved with this simulator. This is an acceptable update rate when low performance aircraft are being modelled. A photograph of the simulator can be seen in figure 1.

2.1 Simulator Hardware

As mentioned previously the simulator was implemented on an IBM PC–AT. A full description of the hardware required for the simulator ~~is given~~ includes: below:

- IBM PC–AT 80286 computer with 80287 mathematics co-processor;
- Locus System Engineering touch screen;
- MetraByte DASH–8 eight channel, 12 bit A/D converter; and
- Measurement System Inc. analogue, spring–centred joystick.

The joystick provided longitudinal and lateral stick and trim switch inputs to the flight dynamic model via the A/D converter. The DASH–8 possesses 3 digital inputs which were used for the trim up and trim down switch inputs. Rudder pedals were not implemented as it was considered that force feedback would be required to make these effective. Force feedback was deemed to be unwarranted for this level of simulator. Power setting and navigation information was input via the touch screen. Section 2.2 describes these aspects more fully.

2.2 Simulator Features and Operation

The flight dynamic model uses the full six degree of freedom flight equations for a fixed wing aircraft. These equations are independent of aircraft type being modelled consequently it is relatively easy to add aircraft models to the simulator. The model has provision for a wind of constant velocity and direction and an atmospheric turbulence model was incorporated. The flight dynamic model is discussed in greater detail in section 2.3.

When the flight simulator is started the operator can specify a number of model parameters. The operator's first choice is the aircraft type. A selection is made between a light aircraft similar to a Beechcraft Bonanza or a small business jet based on data for a Lockheed Jetstar. Next the operator can choose an initial velocity, altitude and heading. The operator can also define the integration time step however the update rate of the instrument display is generally used to set this. This is done to ensure correct real–time operation of the simulator and hence the default value is 0.1 seconds. Next the operator can define a wind speed and direction as well as the atmospheric turbulence intensity. Finally the operator can request plotting of his ground track.

On start-up the operator is provided with a screen displaying an instrument panel which he must use to fly the aircraft and navigate. The flight instruments include the airspeed indicator, attitude indicator, altimeter, turn indicator, climb rate indicator and an engine power indicator. These have the appearance of common aircraft instruments. A throttle lever is not implemented; instead power is varied by touching the power indicator on the screen at the power level required. This is sensed via the touch screen and the dynamic model fades power to this level. This is clearly not a typical aircraft engine instrument.

The navigation instruments available are the automatic direction finder (ADF), distance measuring equipment(DME) and the VHF Omni-directional radio range(VOR). The radio frequencies for these instruments are diplayed digitally on the screen and can be incremented or decremented by touching the screen. Touching the screen above a digit will increment it while touching just below a digit will decrement it. A table of navigational aids for a region of Victoria surrounding Melbourne is kept by the simulator. The operator can then select the frequencies of these navigational aids and fly predetermined courses or approaches to airports. Another feature available in the simulator is plotting of ground track. The simulator includes code to drive a Hewlett Packard 7475A plotter. The plotter begins by drawing all the available navigational aids on the plot and then proceeds to draw the aircraft track.

The keyboard can also be used during run–time to exercise some control over the simulator. The period or full–stop key is used to pause and then restart the simulation. The plus and minus keys can be used to increase and decrease tubulence intensity respectively. Finally the CTRL/A key combination is used to end the simulation.

2.3 Flight Dynamic Modelling

The flight dynamic model incorporates the full six degree of freedom, non–linear flight equations described in Reference 1. The equations use a number of different axes systems. The body axes system is used for the evaluation of rotational equations however flight–path axes are preferred for the translational equations. The aerodynamics of the aircraft are introduced in the stability axes system (i.e. lift, drag, pitching and rolling moments, control inputs etc.). To cope with the lack of rudder pedals, rudder inputs are generated as a fixed fraction of aileron inputs. This provides some measure of turn coordination. Propulsive forces are introduced in the stability axes while the propulsive moments are introduced in the body axes. The equations also permit a steady wind introduced in the earth axes equations.

As suggested in Reference 1, quaternions are used rather than Euler angles. This is necessary to avoid the singularities of the Euler angle system at $\theta = \pm\pi/2$. The equations modified to use quaternions are given in Reference 2. The use of quaternions was necessary for the simulator since aircraft attitudes approaching $\pm\pi/2$ may occasionally be achieved. If the Euler system were used this would result in large errors or even a software failure. Appendix I contains a summary of the flight equations.

Engine modelling in the simulator was maintained at a very simple level. Engine dynamics were not modelled and thrust was computed as:

$$THRUST = POWER \ / \ AIRCRAFT \ VELOCITY$$

Although this is a very crude approximation it was considered to be adequate for this level of simulator. Thrust was also limited to ensure it did not exceed the maximum rated thrust of the engine(s) used in any particular aircraft type. In addition aircraft velocity was limited to prevent a division by zero.

The minimization of computational load in the small computer necessitated the use of a very simple numerical integration scheme for solving the aircraft equations of motion. A first order Euler integration algorithm was used and found to be stable at the 10Hz iteration rate. A second order Runge Kutta integration scheme was investigated; however the increased computation time was not matched by the increased stability and accuracy of this algorithm.

2.3.1 Turbulence Modelling

A model of atmospheric turbulence was also incorporated in the flight dynamic model. The turbulence model was obtained from Reference 3. This is a Mil Spec model for moderate turbulence based on the Mil Spec power spectra for atmospheric turbulence. Given the spectra it is possible to derive first order differential equations which describe the disturbance to the aircraft motion produced by the turbulence. The turbulence model was used to produce disturbances in the vertical(heave), pitch and roll axes of the flight dynamic model. Turbulence is introduced in the $\dot{\alpha}$, $\dot{p}$ and $\dot{q}$ equations(see Appendix I).

The turbulence model requires a source of white noise as its input. An algorithm for a random number generator was sought and Reference 4 describes the random number generator that was used. The computation required to generate white noise at run time was found to be excessive. Instead, a psuedo–random process was provided as follows. White noise inputs for 300 iterations of the flight dynamic model are precomputed and stored in three, 300 element arrays. The turbulence model simply cycles through these arrays at run–time so that at an iteration rate of 10Hz the white noise input repeats every 30 seconds. This is a sufficiently long period to ensure that this is not noticeable.

It was mentioned earlier in this section that the turbulence model describes moderate turbulence however some variability was required. As a result a so–called "turbulence level" was introduced to vary the magnitude of the turbulence. In this way the severity of the turbulence can be varied from zero up to an extreme level. This approach was considered to be acceptable for the purposes of this simulator.

3.0 PROGRAMMABLE COCKPIT – Stage 1(PC-1)

The Programmable Cockpit consists of a group of small computers linked together to represent the controls and displays of a fixed wing aircraft. The flight dynamic model used in the simple system described in section 2 has been modified and extended for use in the PC-1. A CRT display of flight instruments similar to that used in that simple system has also been included in the PC-1. In addition the PC-1 incorporates a number of new diplays simulated on separate computers.

The Programmable Cockpit is the first stage in the development of a rapid prototyping capability. It is intended for use in cockpit display design, cockpit layout studies and crew workload and other human factors studies. Display designs or cockpit layouts can be evaluated in representative cockpit conditions and changed as required. It will also be possible to conduct research not previously possible with existing resources at ARL.

3.1 Programmable Cockpit Features

The Programmable Cockpit uses two Commodore Amiga 2500 computers and one Amiga 500 computer. Each Amiga 2500 contains one 68020 processor and one 80286 processor with their associated co–processors. The Amiga 500 contains one 68000 processor. This is a total of 5 processors driving the complete Programmable Cockpit. These processors are connected by a communication scheme which is described in detail in Reference 6. The system uses a joystick and a throttle lever.

The various components of the Programmable Cockpit are hosted on the five processors. The flight dynamic model runs in the background on an 80286 processor and transmits information to the other processors via the communications. The other processors drive four different displays which consist of the following:

Control Dislay Unit(CDU)	This display is generated by one of the 68020 processors. The monitor used in this display has a touch screen fitted. It includes a CDU used for entering navigational data(i.e. way–point/route entry and selection) as well as engine instruments, heading/altitude bugs and gear up/down selection. In addition a small section of this display acts as an operator console providing some capability to re–initialise the Programmable Cockpit. The CDU is described in greater detail in Reference 5.

Head Down Display(HDD) This is generated by the remaining 80286 processor. This display has two modes of operation referred to as standard and advanced modes. Standard mode is similar to the display used in the original flight simulator(see section 2.0) with the power indicator and the navigational aid frequency displays removed. The advanced display integrates all the separate instruments of the typical display into one display. Reference 7 describes this display in greater detail.

Head Up Display(HUD) This display is generated by the other 68020. It shows a night time, out of the window view of ground lights with a HUD superimposed. This is fully described in Reference 8.

Moving Map Display(MMD) The Amiga 500 generates this display. It includes a digital coastline map which can be scaled up and down together with a digitised 'paper' map of fixed scale. The Amiga 500 is fitted with a touch screen enabling selection of maps and scales and other options. In addition routes entered at the CDU are displayed on the MMD. Reference 9 describes the MMD in greater detail.

Figure 2 shows a photograph of the Programmable Cockpit.

3.2 Extensions to the Flight Dynamic Model

For the Programmable Cockpit a number of extensions and modifications were made to the flight dynamic model. The most significant of these were the modifications to permit take–off and landing. In addition two new aircraft models for an N22B Nomad and a C–5A Galaxy were added. For the C–5A a simple engine model was also incorporated.

Modifications were needed to the flight dynamic model to permit zero and low speeds for take–off and landing. This produces numerical difficulties where divisions by aircraft velocity are used as is the case in the $\dot{\alpha}$ and $\dot{\beta}$ equations. This problem was overcome by defining a limited aircraft velocity, $V_{t_{lim}}$, and arbitrarily setting the minimum speed equal to the stall speed of the aircraft. Similarly a limited aircraft dynamic pressure was also defined. Further restrictions apply to the aircraft's motion once it comes in contact with the ground. Whilst on the ground only forward and pitching motion is possible and pitch attitudes below 0.0 degrees are not permitted. In addition yaw, roll and sideslip are not permitted and angle of attack is constrained to be equal to pitch attitude. These approximations were considered adequate for the purposes of the Programmable Cockpit.

Rolling resistance was assumed to be proportional to the reaction force provided by the ground(i.e. a simple friction model).

$$F_r = \mu . F_{norm}$$

In addition it was necessary to add braking to ensure that the aircraft came to a halt in the length of the runway. As there were no rudder pedals which could be used to initiate braking, a braking force was applied when the pilot throttled back to idle.

The landing and take–off extensions described above result in some rather obvious deficiencies in the model. The first deficiency stems from the absence of an undercarriage model and its associated dynamics. Consequently the actual touch–down is somewhat unrealistic in that the aircraft tends to "stick" to the ground. Another deficiency results from the lack of ground effect modelling so that there is no lift augmentation as the aircraft approaches the ground. The consequence of this is that aircraft exhibits no tendency to "float" when close to the ground.

As mentioned previously a simple engine model was introduced for the C–5A Galaxy model. The intention was not to model the C–5A engines accurately but only to produce gross turbofan engine characteristics. The Galaxy uses four General Electric TF39–GE–1C turbofan engines. Some data on this engine was obtained from "Jane's All The World's Aircraft". A first order lag was used to model engine N1(i.e. RPM of the compressor's first stage). The time constant was varied with N1 to give rapid response at high RPM and slow response at low RPM. Representative values were used for EGT and engine pressure ratio and these were varied with N1.

Other extensions to the model were incorporated to facilitate running in the Programmable Cockpit environment although the capability to run independantly on the IBM PC–AT has been retained. During start–up the operator is asked if the model will be running in the Programmable Cockpit environment or on the IBM PC–AT. The communications data structure was added to the model for data transmission to other elements of the Programmable Cockpit(see Reference 6). As described in section 3.1, the CDU also functions as an operator console and there are five preset flight conditions selectable from the console. When a preset is selected this is transmitted to the flight dynamic model which is then re–initialised to this flight condition. In this way the Programmable Cockpit can rapidly be set up for an approach to an airport, ready for take–off on the end of a runway or any other situation which may be required.

To facilitate development of displays, a debug mode was added to the flight dynamic model. This debug mode can be used to execute single iterations of the dynamic model. In this way problems with displays can be more readily observed. If necessary the data being transmitted via the communications can be collected into a file. This data can then be used off–line to reproduce and correct the problem. Continuous execution of the model can be resumed at any time.

4.0 CONCLUSIONS

The PC–1 represents a useful tool for display design and cockpit layout studies. To facilitate this the flight dynamic model has been significantly extended from the model used in the original simulator. As a research tool for human factors studies it is perhaps of limited value due to the slow display update rates. This tends to make the pilot's task somewhat difficult.

Stage II of the Programmable Cockpit will incorporate a graphics workstation with significantly more computational power than that provided by the Commodore Amigas. It is intended that the HUD and the HDD will be ported to the workstation since these displays require considerable graphics processing. The flight dynamic model may be ported to the 68020 processor of an Amiga 2500. This should provide ample processing for any future extensions. Data will be transmitted to the workstation which can be dedicated to displays such as the HUD.

Further extensions to the flight dynamic model will be required for Stage II. It is likely that rudder pedals will be incorporated with some form of feel system. The model may need to compute the forces that are fed back to the rudder pedals. Some of the limitations discussed in section 3.1 will need to be addressed. The incorporation of an undercarriage model and some form of ground effect will be necessary to achieve the level of realism required for Stage II.

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APPENDIX I

PART 1 - AIRCRAFT FLIGHT EQUATIONS

Aircraft attitude is defined using quaternions rather than Euler angles(see Reference 1). The quaternion rate equations are:

$$\dot{\tau}_0 = -0.5(p.\tau_{1_n} + q.\tau_{2_n} + r.\tau_{3_n}) \quad (1)$$
$$\dot{\tau}_1 = 0.5(p.\tau_{0_n} - q.\tau_{3_n} + r.\tau_{2_n}) \quad (2)$$
$$\dot{\tau}_2 = 0.5(p.\tau_{3_n} + q.\tau_{0_n} - r.\tau_{1_n}) \quad (3)$$
$$\dot{\tau}_3 = -0.5(p.\tau_{2_n} - q.\tau_{1_n} - r.\tau_{0_n}) \quad (4)$$

Transformation of variables from body axes to earth axes is done using direction cosines which are computed as follows:

$$L_1 = 2({\tau_{0_n}}^2 + {\tau_{1_n}}^2) - 1 \quad (5)$$
$$L_2 = 2(\tau_{1_n}.\tau_{2_n} + \tau_{0_n}.\tau_{3_n}) \quad (6)$$
$$L_3 = 2(\tau_{1_n}.\tau_{3_n} - \tau_{0_n}.\tau_{2_n}) \quad (7)$$
$$M_1 = 2(\tau_{1_n}.\tau_{2_n} - \tau_{0_n}.\tau_{3_n}) \quad (8)$$
$$M_2 = 2({\tau_{0_n}}^2 + {\tau_{2_n}}^2) - 1 \quad (9)$$
$$M_3 = 2(\tau_{2_n}.\tau_{3_n} + \tau_{0_n}.\tau_{1_n}) \quad (10)$$
$$N_1 = 2(\tau_{1_n}.\tau_{3_n} + \tau_{0_n}.\tau_{2_n}) \quad (11)$$
$$N_2 = 2(\tau_{2_n}.\tau_{3_n} - \tau_{0_n}.\tau_{1_n}) \quad (12)$$
$$N_3 = 2({\tau_{0_n}}^2 + {\tau_{3_n}}^2) - 1 \quad (13)$$

and Euler angles can be derived from the direction cosines.

$$\theta = tan^{-1}\left(\frac{-L_3}{(L_1^2 + L_2^2)^{\frac{1}{2}}}\right) \quad (14)$$
$$\phi = tan^{-1}\left(\frac{M_3}{N_3}\right) \quad (15)$$
$$\psi = tan^{-1}\left(\frac{L_2}{L_1}\right) \quad (16)$$

The force equations are defined in the stability axes:

$$F_{X_{stab}} = X_p.cos\alpha + Z_p.sin\alpha + X_a + X_{g_{stab}} \quad (17)$$
$$F_{Y_{stab}} = Y_p + Y_a + Y_{g_{stab}} \quad (18)$$
$$F_{Z_{stab}} = Z_p.cos\alpha - X_p.sin\alpha + Z_a + Z_{g_{stab}} \quad (19)$$

where the components of aircraft weight resolved into stability axes are given by:

$$X_{g_{stab}} = L_3.mg.cos\alpha + N_3.mg.sin\alpha \quad (20)$$
$$Y_{g_{stab}} = M_3.mg \quad (21)$$
$$Z_{g_{stab}} = -L_3.mg.sin\alpha + N_3.mg.cos\alpha \quad (22)$$

The forces in air–path axes can be obtained from the stability axes forces in the following manner:

$$F_{X_w} = F_{X_{stab}}.cos\beta + F_{Y_{stab}}.sin\beta \quad (23)$$
$$F_{Y_w} = -F_{X_{stab}}.sin\beta + F_{Y_{stab}}.cos\beta \quad (24)$$
$$F_{Z_w} = F_{Z_{stab}} \quad (25)$$

The translational equations for the aircraft in air–path axes are shown below:

$$m.\dot{V}_t = F_{X_w} \quad (26)$$
$$m.V_t.R_w = F_{Y_w} \quad (27)$$
$$-m.V_t.Q_w = F_{Z_w} \quad (28)$$

From the above equations it is possible to derive equtions for $\dot{\alpha}, \dot{\beta}$ and $\dot{V}_t$.

$$\dot{\beta} = \frac{F_{Y_w}}{m.V_t} - r_{stab} \quad (29)$$
$$\dot{\alpha} = \left(q.cos\theta - p_{stab}.sin\beta + \frac{F_{Z_w}}{m.V_t}\right)/cos\beta \quad (30)$$
$$\dot{V}_t = \frac{F_{X_w}}{m} \quad (31)$$

The total moments acting on an aircraft usually consist of aerodynamic and propulsive components. Aerodynamic moments are often given in stability axes whereas propulsive moments are normally given in body axes. Consequently the total moment equations take the form shown below:

$$L = L_a.cos\alpha - N_a.sin\alpha + L_p \quad (32)$$
$$M = M_a + M_p \quad (33)$$
$$N = L_a.sin\alpha + N_a.cos\alpha + N_p \quad (34)$$

Using the total aircraft moments the body axes angular accelerations can be computed.

$$\dot{p} = L.C_1 + N.C_2 + (p.C_3 + r.C_4).p \quad (35)$$
$$\dot{q} = M.C_5 + (r^2 - p^2).C_6 + r.p.C_7 \quad (36)$$
$$\dot{r} = N.C_8 + L.C_2 + (p.C_9 - r.C_3).q \quad (37)$$

where

$$C_0 = I_{XX}.I_{ZZ} - I_{XZ}^2 \tag{38}$$
$$C_1 = \frac{I_{ZZ}}{C_0} \tag{39}$$
$$C_2 = \frac{I_{XZ}}{C_0} \tag{40}$$
$$C_3 = C_2.(I_{XX} - I_{YY} + I_{ZZ}) \tag{41}$$
$$C_4 = C_1.(I_{YY} - I_{ZZ}) - C_2.I_{XZ} \tag{42}$$
$$C_5 = \frac{1}{I_{YY}} \tag{43}$$
$$C_6 = C_5.I_{XZ} \tag{44}$$
$$C_7 = C_5.(I_{ZZ} - I_{XX}) \tag{45}$$
$$C_8 = \frac{I_{XX}}{C_0} \tag{46}$$
$$C_9 = C_8.(I_{XX} - I_{YY}) + C_2.I_{XZ} \tag{47}$$

After integrating the equation for $\dot{V}_t$ it is possible to compute the body axes components of the aircraft velocity relative to the surrounding air mass.

$$U_{body} = V_t.cos\alpha.cos\beta \tag{48}$$
$$V_{body} = V_t.sin\beta \tag{49}$$
$$W_{body} = V_t.sin\alpha.cos\beta \tag{50}$$

The northerly, easterly and downward components of aircraft velocity relative to the earth are then computed and wind components are introduced.

$$V_{N_{earth}} = L_1.U_{body} + M_1.V_{body} + N_1.W_{body} - V_{N_{wind}} \tag{51}$$
$$V_{E_{earth}} = L_2.U_{body} + M_2.V_{body} + N_2.W_{body} - V_{E_{wind}} \tag{52}$$
$$V_{D_{earth}} = L_3.U_{body} + M_3.V_{body} + N_3.W_{body} - V_{D_{wind}} \tag{53}$$

These velocities can be integrated to determine aircraft position.

PART 2 - MODIFICATIONS FOR TURBULENCE

The original equations for $\dot{\alpha}$, $\dot{p}$ and $\dot{q}$ are given by equations 30, 35 and 36 respectively. With turbulence inputs added the equations become:

$$\dot{\alpha} = \left(q.cos\theta - p_{stab}.sin\beta + \frac{F_{Z_w}}{m.V_t}\right)/cos\beta + \dot{\alpha}_{turb}.K_{atten} \tag{54}$$
$$\dot{p} = L.C_1 + N.C_2 + (p.C_3 + r.C_4).p + \dot{p}_{turb}.K_{atten} \tag{55}$$
$$\dot{q} = M.C_5 + (r^2 - p^2).C_6 + r.p.C_7 + \dot{q}_{turb}.K_{atten} \tag{56}$$

where K_{atten} is used to vary the magnitude of the turbulence and $\dot{\alpha}_{turb}, \dot{p}_{turb}$ and $\dot{q}_{turb}$ are computed in the turbulence equations.

FIGURE 1 IBM PC-AT BASED SIMULATOR

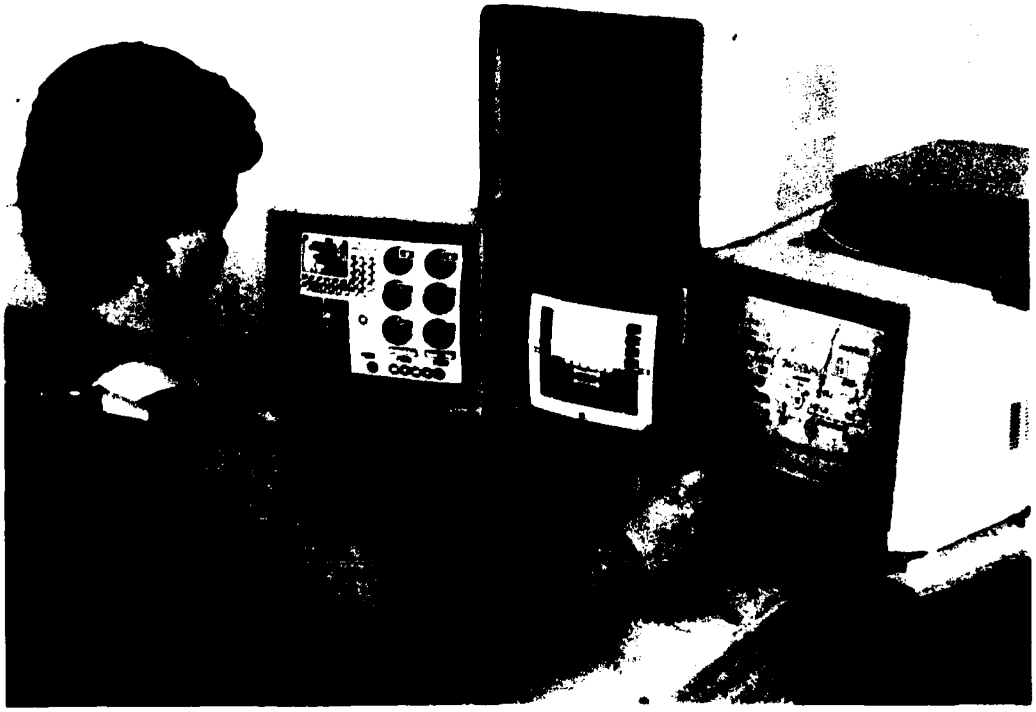

FIGURE 2 PROGRAMMABLE COCKPIT

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16. ABSTRACT
The Programmable Cockpit has been developed as a low cost alternative to a full research simulator. It is intended for use in cockpit display design and layout studies and for crew workload and other human factors studies. With this system it is possible to quickly change the design or layout of a display and evaluate it under representative flight conditions.

A six degree of freedom flight dynamic model has been developed for the Programmable Cockpit. The model's development is described from its original form in the IBM PC-AT Simulator to its current implementation in the Programmable Cockpit. Its features and operation are described in some detail as well as its limitations. A brief overview of the Programmable Cockpit is also given.